APPLICATION NOTE

Why is Oscilloscope Vertical Accuracy Important?

Evaluating Oscilloscope Signal Accuracy

KEYSIGHT

What Does “Vertical Accuracy” Mean?

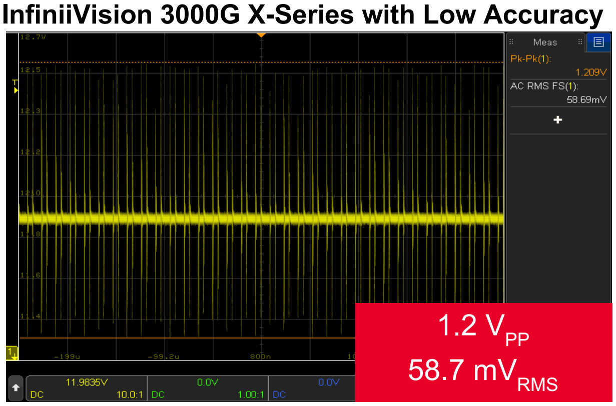
The horizontal axis of an oscilloscope is the time base (seconds per division or s/div) and the vertical axis shows us the voltage (volts per division, V/div). Vertical accuracy refers to the accuracy of the voltage we are seeing on screen. Both visually and in measurements. How close is the voltage I am reading on the oscilloscope screen to the actual voltage of my signal? This is all going to depend on the vertical accuracy.

Highest ADC bits + Lowest Noise Floor = Highest Vertical Accuracy

Vertical accuracy can be defined by two key specifications: 1. The number of ADC bits, and 2. The front-end noise floor of the oscilloscope. The higher the number of ADC bits, the more vertical resolution you have. The more vertical resolution you have, the more accurate of a signal you see. Furthermore, the lower your front-end noise floor is, the less your oscilloscope impacts the signal you are measuring. All oscilloscopes have some intrinsic noise, it’s completely unavoidable, just like every electronic device has *some* noise. Any noise present in the oscilloscope is going to ride on top of your signal and skew your measurements. You want an oscilloscope with the least amount of noise possible so that it is not impacting your measurements. This is important to consider with any type of signal, but even more critical when measuring very small voltages.

Using an oscilloscope with a lower ADC and high noise floor can cause inaccurate measurement and lead to redesigns, re-sourcing components, and ultimately wasting valuable time. To minimize the time you spend validating and redesigning, it’s important to evaluate an oscilloscope’s vertical accuracy to ensure you can trust the measurements you are making. You can see below that high vertical accuracy not only makes a difference visually, but it also makes a significant difference in the voltage measurements.

InfiniiVision 3000G X-Series with Low Accuracy



New HD3 Series with High Vertical Accuracy

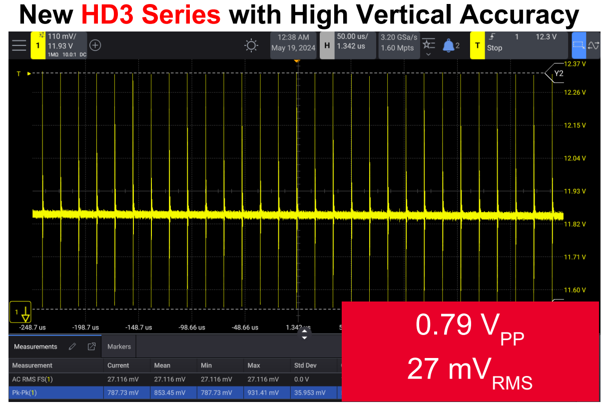


Figure 1. Power supply noise and ripple – measuring the exact same signal on both oscilloscopes with the same probing setup, we see much more accurate measurements on the HD3 Series than we do on the “older” 3000G/4000G X-Series oscilloscopes. The HD3 has significantly higher vertical resolution with the industry’s only 14 bits ADC, and the lowest noise floor in class at 50 uV_{RMS}. The 3000G has only 8 bits and a whopping 250 uV_{RMS} of noise. We can see what a difference that makes in these measurements.

ADC Bits and Minimum Resolution

A key technology block for vertical signal accuracy is the analog-to-digital converter (ADC). The higher the number of ADC bits, the more resolution the oscilloscope has. A 14-bit ADC ideally provides **64 times the resolution** as a scope with an 8-bit ADC.

Resolution is the smallest quantization level determined by the analog-to-digital converter (ADC) in the oscilloscope. A scope's ADC with a resolution of 8 bits can encode an analog input to one in 256 different levels, since $2^8 = 256$. We'll refer to these as quantization or Q-levels.

The ADC operates on the scope's full scale vertical value. For both current and voltage measurements, the Q-level steps are associated with the full-scale vertical scope setting. If the user adjusts the vertical setting to 100 mV per division, full screen equals 800 mV (8 divisions * 100 mV/div) and Q-level resolution is equal to 800 mV divided by 256 levels, or 3.125 mV.

Let's look at a specific example as shown in Figure 2. Two scopes are both scaled to 800 mV full screen. A scope with an 8-bit ADC has resolution of 800 mV/(2^8 = 256 Q levels), or 3.125 mV. A scope with a 14-bit ADC, like the HD3 Series, has resolution of 800 mV/(2^{14} = 4096 quantization levels), or 48.8 µV. Each scope can only resolve signals down to the smallest Q level.

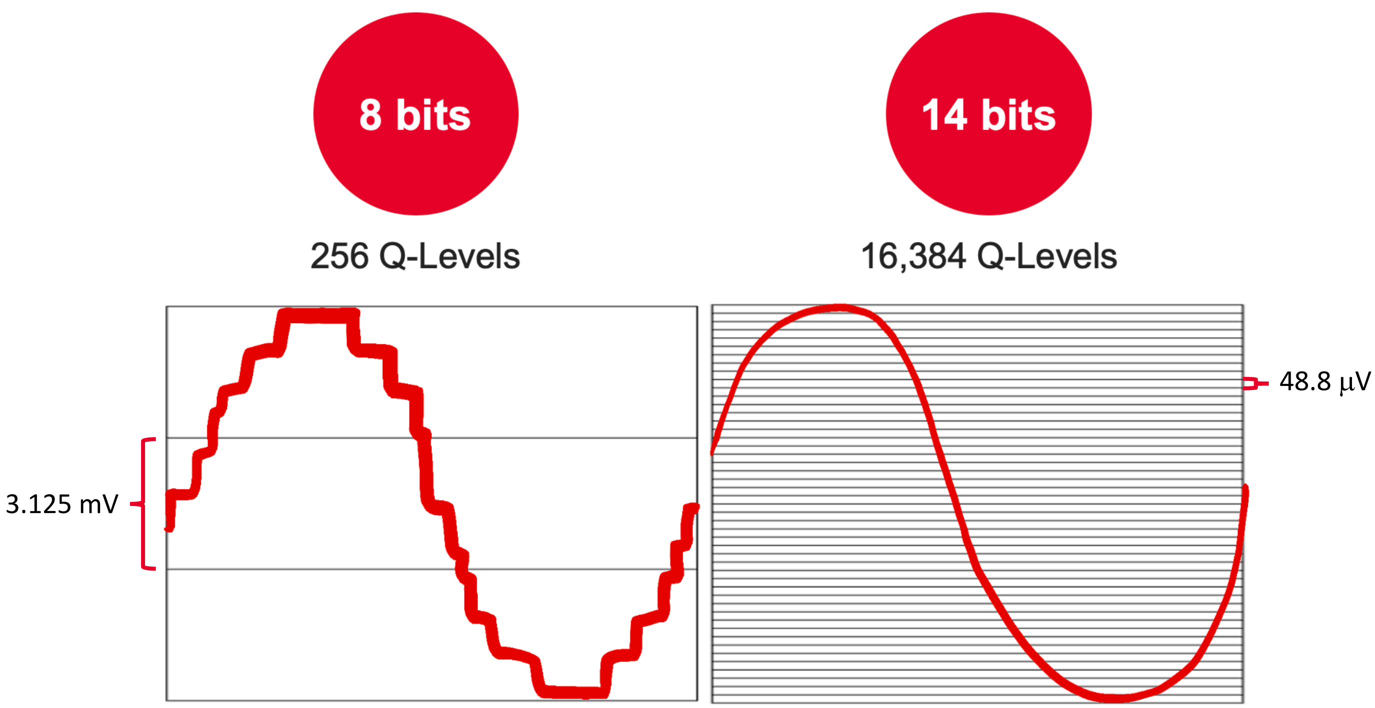


Figure 2. While most oscilloscopes use 8 to 12 bit ADCs, the HD3 Series is the first in the industry to offer an astounding 14 bits of resolution. This is 4x the resolution of a 12 bit ADC and 64x the resolution of an 8 bit. Higher ADC + low noise = higher resolution!

Many oscilloscopes also offer high-resolution mode. Oversampling techniques combined with DSP filters can increase vertical resolution. Vendors often refer to this increase in terms of "bits of resolution." In the case of InfiniiVision HD3 Series, high-res increases bits of resolution from 14-bits (native ADC resolution) to 16-bits of resolution. This technique requires an ADC that has been architected with excess sample rate relative to the hardware bandwidth needed for a particular measurement.

A high number of ADC bits will theoretically increase resolution. However, that is not always the case. Vertical resolution is not only dependent on the ADC as we learned above, it is also dependent on the front-end noise of the oscilloscope. The effective number of bits (ENOB) specification take the noise of the system into account and will tell you how many of those bits are actually effective in making measurements. Not only does the HD3 Series have the highest ADC (14 bits) and lowest noise (50 μV), but it also has the highest ENOB in this class. Be sure to learn more about ENOB in the section below, and in the Understanding ADC Bits and ENOB white paper.

ENOB (Effective Number of Bits)

Effective number of bits (ENOB) is a measure of the dynamic performance. While some oscilloscope vendors may give the ENOB value of the oscilloscope's ADC by itself, this figure has no value. ENOB of the entire system is what is important. While the ADC could have a great ENOB, poor oscilloscope front-end noise would dramatically lower the ENOB of the entire measurement system. While oscilloscope vendors generally don't publish overall ENOB values, they typically do characterize it and will provide these values when requested for a specific model number.

Oscilloscope ENOB isn't a specific number, but rather a series of curves. ENOB is measured as a fixed amplitude sine wave is swept in frequency. Each curve is created at a specific vertical setting while frequency is varied. The resulting voltage measurements are captured and evaluated. Using time-domain methods, ENOB is calculated by subtracting the theoretical best fit sine wave from what was measured. The error between these curves can come from the front-end of the oscilloscope from attributes such as phase non-linarites and amplitude variations over frequency sweeps. Error can also come from interleaving distortion from ADCs. Evaluating the same signal in the frequency domain, ENOB is calculated by subtracting the power associated with the primary tone from the entire broadband power. Both techniques provide the same result.

ENOB values will be lower than the oscilloscope's ADC bits. For example, the 8-bit InfiniiVision 3000G/4000G X-Series scopes have a system ENOB of about 6.9. A 14-bit HD3 Series oscilloscope with an extremely low noise front end has a system ENOB of over 10.4 bits.

In general, a higher ENOB is better. However, a couple cautions need to accompany engineers who look exclusively at ENOB to gauge signal integrity goodness. ENOB doesn't take into account offset errors or phase distortion that the scope may inject.

Learn more about the importance of ENOB and how it differs from ADC bits in the white paper Understanding ADC Bits and ENOB.

Scaling Impact on Resolution

Scaling has a huge impact on getting the most resolution from your oscilloscope. Scaling the waveform to take the whole display of the scope enables the scope's analog-to-digital (ADC) converter. If a signal is scaled to take up only ½ of the vertical display, you've just decreased the number of ADC bits being used from 14 to 12. Scale the waveform to ¼ of the vertical display and you've reduced the number of ADC bits used from 14 to 10. Scale the waveform to take close to consuming full vertical display and now you are using all 14 bits of the oscilloscope's ADC. To get the best resolution, use the most sensitive vertical scaling setting while keeping the waveform on the display.

The combination of the ADC, the scope's front-end architecture, and the probe determine how sensitive the vertical scaling can be. At a certain point, the hardware in an oscilloscope cannot reach a lower vertical scale setting—even though the knobs of the scope allow you to dial a smaller setting. Vendors will often refer to this as the point where the scope moves into software magnification. Turning the scope's vertical scale to a smaller number simply magnifies the displayed signal and doesn't result in any additional resolution as the user would naturally expect. Most traditional scopes employ software magnification below 2 mV/div. Additionally, some scope vendors bandwidth limit at small vertical settings (below 2 mV/div). This is because their scopes have significant front-end noise that would make it near impossible to see small signals at full bandwidth.

Let's compare two scopes as an example. A small signal has magnitude such that a vertical scaling of 16 mV full screen allows the signal to consume almost all the vertical display height.

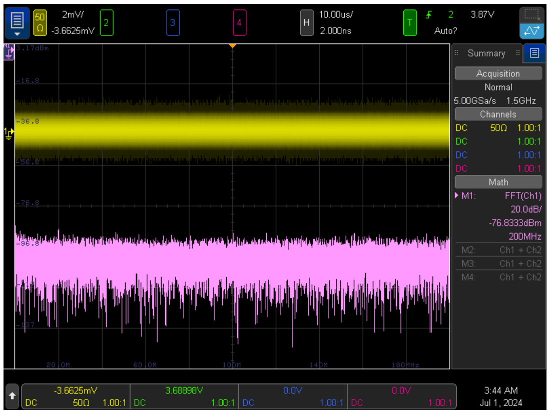
- A traditional scope such as the Keysight InfiniiVision 3000G/4000G X-Series scopes has an 8-bit ADC and goes into SW magnification at 7 mV div. Minimal full screen resolution equals 56 mV (7 mV/div * 8 div)/256 Q levels. This results in minimum resolution of 218 μV.
- The InfiniiVision HD3 Series oscilloscope has the industry's only 14-bit ADC and stays in hardware all the way down to 2 mV/div with no required bandwidth reduction. Minimal full screen resolution equals 16 mV (2 mV/div * 8 div)/16,384 Q levels. This results in minimum resolution of 0.15 nV — 64 times the resolution as the traditional 8-bit scope as shown in as shown in Figure2.

Oscilloscope Noise

Having a scope with low noise (high dynamic range) is critical for visibility to small currents and voltages, or to see small changes on larger signals.

Note: You won't be able to see signal detail smaller than the noise level of the scope. When a signal is "in the noise" it means it is smaller than the noise floor (figure 3).

InfiniiVision 3000G X-Series with High Noise **New HD3 Series with the Lowest Noise**



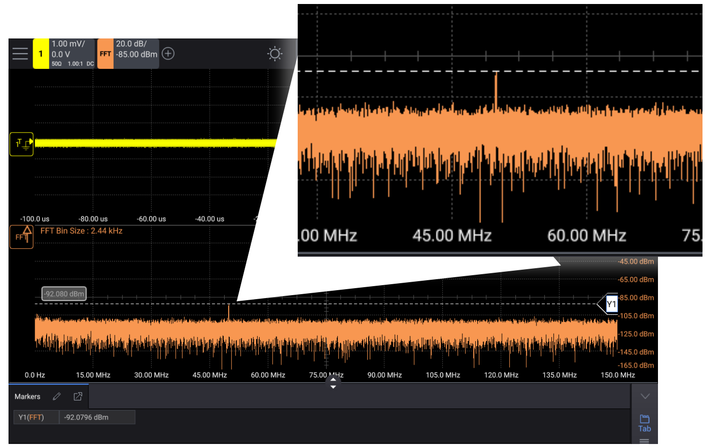


Figure 3. In this example we are measuring a 53 µV signal. On the left, we are measuring with a 3000G X-Series. At 2mV/div the 3000G has a noise floor of 372 μV_{RMS}, so it is not physically possible to see a 53 µV.tone on the FFT of this oscilloscope. There is just too much noise coming from the oscilloscope front-end channels. We can't even see the tone in the FFT on the left. **On the right side we are measuring with an HD3 Series**, which at these settings has a noise floor of less that 50 μV_{RMS}. We can very clearly see that extremely small 53 µV.tone on the FFT of the HD3 Series because the front-end noise is low enough. You want the least amount of oscilloscope noise so that you can capture every part of your signal, even the smallest parts!

If noise levels are higher than ADC quantization levels, users won't be able to take advantage of the additional ADC bits.

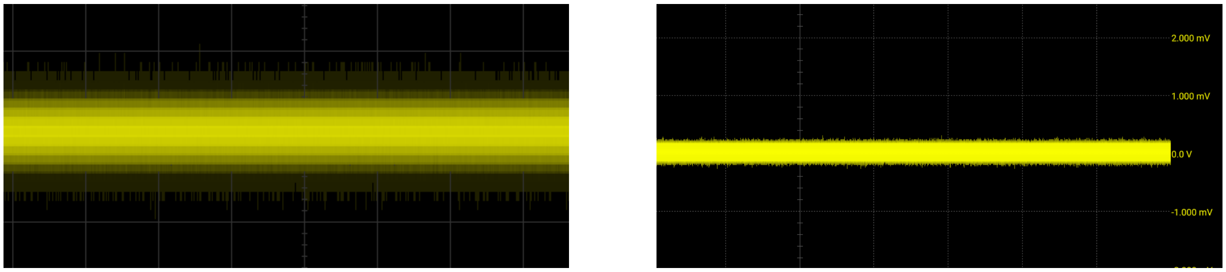
Noise can come from a variety of sources, including the front end of the scope, the ADC in the scope and the probe or cable used connected to the device. The ADC itself has quantization error. For oscilloscopes, quantization noise typically plays a lesser role in contribution of overall noise and the front end of the oscilloscope plays a more significant role.

Most oscilloscope vendors will characterize noise for specific bandwidths and include these values on the product data sheet. If not, you can ask for the information, or find out yourself. It's easy to measure in a few minutes. Disconnect all inputs from the front of the scope and set the scope to 50 Ω input path. You can also run the test for the 1 MΩ path. Turn on a decent amount of acquisition memory such as 1 Mpt, with sample rate fixed at high sample rate to ensure you are getting the full scope bandwidth. Run the scope with infinite persistence and see how thick the resulting waveform is. The thicker the waveform, the more noise the scope is producing internally. You can turn on an "AC RMS (full screen std. deviation)" to see what the noise level is at each V/div setting.

The InfiniiVision HD3 Series oscilloscope was designed with an all-new custom front-end with the lowest noise floor in this class (<50uV$_{RMS}$ at 2 mV/idv, 50 Ohm).

InfiniiVision 3000G X-Series with High Noise

New HD3 Series with the Lowest Noise



372 µV_{RMS}

31.5 µV_{RMS}

Figure 4. This AC RMS noise measurement was made at 1mV/div and the 50Ohm path on each oscilloscope. This base level noise of the oscilloscope is going to ride on top of every signal you measure. Keep that in mind with competitor oscilloscopes as well! This can make a huge difference in your measurements. The front-end channels of the HD3 Series were custom designed to have the lowest noise in the industry to impact your signals and measurements as little as possible.

Each scope channel will have unique noise qualities at each vertical setting. You can view the noise visually just by looking at wave shape thickness, or you can be more analytical and take a Vrms AC measurement to quantify. Create a chart like the one shown in Figure 7. These measurements will enable you to know how much noise each scope channel has at various vertical settings to measure signals that are less than the noise of the scope. All acquiredvertical values are subject to deviation up to the noise value of the scope. Noise impacts both horizontal as well as vertical measurements.

The lower your oscilloscope's noise, the better the measurement results will be.

Frequency Responses

Each oscilloscope model will have unique frequency response that is a quantitative measure of the scope's ability to accurately acquire signals up to the rated bandwidth. Three requirements must be kept in order for oscilloscopes to accurately acquire waveforms.

1. The oscilloscope must have a flat frequency response.
2. The oscilloscope must have a flat phase response.
3. Captured signals must be in the bandwidth of the oscilloscope.

Deviation from one or more of these requirements will cause an oscilloscope to inaccurately acquire and draw a waveform. The more variance from these requirements, the greater the error in acquiring and drawing the waveform.

Fast edges contain multiple harmonics, and scope users expect the oscilloscope to accurately measure each harmonic component using the correct magnitude. Ideally oscilloscopes would have a uniform flat magnitude response up to the bandwidth of the scope, with the signal delayed by precisely the same amount of time at all frequencies (phase). Flat frequency responses indicate that the oscilloscope is treating all frequencies equally, and without a flat phase response the scope will show distorted waveforms.

The HD3 Series oscilloscopes use correction filters to produce an extremely flat magnitude and phase response.

A frequency response that is not flat will cause distortions in the displayed signal. You can ask your oscilloscope vendor to provide a frequency response for an oscilloscope you are considering. These plots are typically not in data sheets but can be made available.

Your scope's overall frequency response will be a combination of the oscilloscope's frequency response combined with the frequency response of any probes or cables connected between the device under test and the instrument. If you put a BNC cable that has bandwidth of 1.5 GHz on the front of a 4 GHz scope, the overall bandwidth of the system is limited by the 1.5 GHz BNC cable and not the oscilloscope. The same principle applies for probes and accessories that attach to the probes. Probes and cables also have their own frequency response. If you need to make a precision measurement, make sure your probes, accessories, and cables aren't the limiting factor.

Correction Filters

Some oscilloscopes have strictly analog front-end filters that determine frequency response, while others apply correction filters in real time. Correction filters are typically implemented in hardware DSP blocks and are tuned for a particular family of oscilloscopes to create a flat magnitude and phase response. Combining correction filters with frontend analog filters creates flatter magnitude and phase responses verses raw analog filters alone. Oscilloscopes of superior quality, like the HD3, include both analog as well as correction filters to create a uniform and flat frequency response.

Frequency response shapes generally are named by their roll-off characteristics. Responses that have brick-wall filters are desired as they produce less noise by more quickly attenuating out-of-band noise. For fast edges, out-of-band higher harmonics are quickly attenuated resulting in slight under- and over-shoot. Responses that have a Gaussian roll-off don't show as much ringing, but with the trade-off is additional noise.

Summary

When evaluating a new oscilloscope, it is critical to ensure you will see the best view of your signals under test over a wide frequency range. Make sure you choose an oscilloscope that has strong characteristics across all attributes of signal accuracy: high resolution, low noise, flat frequency response, and high ENOB. The InfiniiVision HD3 Series offers the lowest noise front-end in class with the highest ADC in the industry at an astounding 14 bits. If you're concerned about the accuracy of what you are seeing on the scope screen, look no further than the HD3.

Vertical Accuracy Metric	Scope Technology Block	Where can you find the answer?
Resolution	Analog to Digital Converter (ADC)	Product datasheet
Noise	Front-end channels	Product datasheet
Effective Number of bits (ENOB)	ADC/Front-end	Some vendors include this, others don't. If you don't find this information in the datasheet, be sure to ask for it
Hardware Vertical Scaling	ADC/Front-end	Data sheets don't always specify when software magnification starts. Some vendors bandwidth limit at small sensitivities.
Frequency Response Flatness	Analog filters and correction filters	Not typically included in product datasheets. You will need to ask the vendor to see a magnitude and phase response for the model you are evaluating
Time scale accuracy	Time base	Product datasheet

Glossary

ADC (Analog to Digital Converter)

Device in oscilloscope that converts voltage to a digital amplitude value. Total quantization or output levels of the ADC will equal 2^n where n equals the number of ADC bits.

Bits of resolution

Bits of resolution defines total potential output levels the oscilloscope can create using ADC bits, high-resolution mode, and/or averaging.

ENOB (Effective number of bits)

The dynamic range of an ADC or oscilloscope is often summarized in terms of its effective number of bits (ENOB). ENOB accounts for noise and a number of other sources of vertical distortion. The ENOB of the scope's ADC will be greater than the scope's overall ENOB.

Filter

A filter is a circuit or algorithm with specific frequency response characteristics. Filters can be implemented from discrete analog circuits, done in hardware where they are referred to as DSP hardware filter, or can be performed more slowly but with greater flexibility in software.

Frequency response

The frequency response describes the magnitude or phase characteristics of an oscilloscope over a specific bandwidth range. Ideal frequency response plots are flat with a brick-wall roll-off.

Front end

Front end describes the oscilloscope circuitry between the BNC input on the oscilloscope and the scope's ADC. The front-end includes analog filters, switching between 1 MΩ and 50 Ω paths, and attenuation required to scale the signal properly for the ADC.

Jitter

Jitter describes deviation from ideal horizontal position. Oscilloscopes are great tools for measuring jitter of target systems. Scopes also inherently include jitter sources internal to the scope that contribute to jitter measurements.

Noise

Noise is vertical deviation from a true signal value. You won't be able to see signal detail smaller than the noise level of the scope. If noise levels are higher than ADC quantization levels, users won't be able to take advantage of the additional ADC bits. The front end tends to be the most significant contribution of oscilloscope noise.

Resolution

Resolution for a scope ADC is the smallest quantization level determined by the analog-to-digital (A/D) converter in the oscilloscope. Oscilloscopes can achieve smaller resolution through averaging where points in time across multiple acquisitions are averaged, or high-res mode where oversampling combined with a DSP filter enables more resolution.

Time base

The time base is the circuitry in the oscilloscope responsible for horizontal accuracy and keeping sample clock jitter low.

Related Literature

Publication Title	Publication Number
InfiniiVision HD3 Series Oscilloscope Datasheet	TBD
Understanding ADC and ENOB – White Paper	
How to Make Ripple and Noise Measurements	5992-0946
Oscilloscope Measurement Tools to Debug Automotive Serial Buses Quickly Using the HD3 Series	5991-0512

See What You've Been Missing

4x the resolution and up to 10x less noise

The HD3 Series brings Keysight's industry-leading capabilities from high-performance scopes to the high-volume level, making precision portable from 200 MHz to 1 GHz. Leveraging custom hardware technology from the UXR Series, the HD3 boasts the most impressive resolution on the market with 4x the vertical accuracy and up to 10x less noise than the competition. Paired with our fast, uncompromised waveform update rate and 25x more memory, the HD3 Series is truly set apart from other oscilloscopes in this class.

Learn more about the portable precision of the HD3 at keysight.com/find/HD3

Figure 5. The all-new HD3 Series, built of completely custom components optimized specifically for oscilloscope measurements.